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Feasibility study on HYSOL CSP

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Abstract

Concentrating Solar Power (CSP) plants utilize thermal conversion of direct solar irradiation. A trough or tower configuration focuses solar radiation and heats up oil or molten salt that subsequently in high temperature heat exchangers generate steam for power generation. High temperature molten salt can be stored and the stored heat can thus increase the load factor and the usability for a CSP plant, e.g. to cover evening peak demand. In the HYSOL concept (HYbrid SOLar) such configuration is extended further to include a gas turbine fuelled by upgraded biogas or natural gas. The optimised integrated HYSOL concept, therefore, becomes a fully dispatchable (offering firm power) and fully renewable energy source (RES) based power supply alternative, offering CO_2-free electricity in regions with sufficient solar resources.

The economic feasibility of HYSOL configurations is addressed in this paper. The CO_2 free HYSOL alternative is discussed relative to conventional reference firm power generation technologies. In particular the HYSOL performance relative to new power plants based on natural gas (NG) such as open cycle or combined cycle gas turbines (OCGT or CCGT) are in focus. The feasibility of renewable based HYSOL power plant configurations attuned to specific electricity consumption patterns in selected regions with promising solar energy potentials are discussed

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Keywords: Feasibility analysis; CSP, Hybridization; Storage; Steam turbine; Firm power; HYSOL; OCGT; CCGT

1. Introduction

Concentrating Solar Power (CSP) plants utilize thermal conversion of direct solar irradiation. A trough or tower configuration focuses solar radiation and heats up oil or molten salt that subsequently in high temperature heat exchangers generates steam for power generation. High temperature molten salt can be stored and the stored heat can thus increase the load factor and the usability for a CSP plant, e.g. to cover night (peak) demand. In the HYSOL concept (HYbrid SOLar) such configuration is extended further to include a gas turbine fuelled by upgraded biogas or natural gas. The optimised integrated

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HYSOL concept, therefore, becomes a fully dispatchable (offering firm power) and a fully renewable energy (RES) based power supply alternative, offering CO_2-free electricity in regions with sufficient solar resources.

The economic feasibility of HYSOL configurations is addressed in this paper. The CO_2 free HYSOL alternative is discussed relative to conventional reference firm power generation technologies. In particular the HYSOL performance relative to new power plants based on natural gas (NG) such as open cycle or combined cycle gas turbines (OCGT or CCGT) is in focus. The feasibility of renewable based HYSOL power plant configurations attuned to specific electricity consumption patterns in selected regions with promising solar energy potentials are discussed.

1.1. Example studied

The analytical approach used is illustrated from an example where a HYSOL configuration is optimised to conditions seen e.g. in the Kingdom of Saudi Arabia (KSA). Thus, the HYSOL Power Plant studied has been attuned to solar potentials and power system characteristics resembling conditions in the Kingdom of Saudi Arabia (KSA).

The KSA HYSOL plant configuration particularizes the basic HYSOL outline by the choices:

- A CSP Tower configuration has been assumed. HYSOL configurations can also be applied with CSP trough design.
- No biogas plant and biogas supply have been assumed for this KSA case. HYSOL's 100% renewable configuration would have a biogas plant included and would use biogas upgraded to NG quality.

The KSA HYSOL configuration analysed uses natural gas (NG) and not biogas based methane, and may thus not be termed fully renewable, - though being a firm, fully dispatch-able and mainly renewables based power plant.

1.2. The HYSOL alternative and competing technology

This paper compares electricity production costs for a HYSOL plant alternative to production cost for conventional power plant solutions or reference plants. In this KSA case it has been assumed that the main competing reference technologies are an Open Cycle Gas Turbine (OCGT) and an Combined Cycle Gas Turbine (CCGT) using natural gas (NG).

2. Approach and basic assumptions

2.1. Economic indicator

Basically a socio-economic approach is applied. And generally main focus is placed on the economic indicator LCOE (the levelized cost of electricity), and on the sensitivity of the LCOE in particular to variations in the two parameters:

- load factor or the number of full load hours per year, and the
- price of natural gas (given as the levelized NG price covering the period analysed)

The solar potential and the annual power production heavily impact the HYSOL power plant economy. And for fossil based competing reference technologies fuel cost and CO_2 emission cost developments constitute important framework conditions. LCOE dependency on in particular these major parameters will be in focus in this study of (predominantly) renewable energy source (RES) based HYSOL solutions relative to fossil based conventional reference power plant solutions.

2.2. Base Case assumptions

For the present socio-economic analyses the following general assumptions have been adopted as 'Base Case':

Price level:		Year 2015
Socio economic rate of calculation (rate of interest):		4 % p.a.
Project base year:		2020
Period analysed:	Time period:	2021-2045
	Period in years:	25 years

Chosen Base Case for the KSA HYSOL plant annual production, assigned capacity and load factor are:

Annual electricity production:	812.7	GWh/year
Assigned HYSOL capacity (P_H):	$P_H =$	$130 MW_{el}$
Annual full load hours (H_{FLH}) and Load factor (LF):		
$H_{FLH} =$ 812.7GWh / 130MW =	6251	hours/year
and LF= 6251/8760=	0.714	

As mentioned, gas consumed in the KSA HYSOL gas turbine (GT) component is assumed to be natural gas (NG). The KSA Base Case NG price and the sensitivity variations analysed for the NG price are:

NG price	Base case:	13.65 \$/MWh (4\$/MMBtu)
	Sensitivity:	Base Case +/- 20%, +/-40%

Data on investments, operation and maintenance costs for the KSA HYSOL configuration are found in the Appendix**.**

2.3. Base Case overview and issues addressed via sensitivity analyses

Electricity production costs (LCOE) are furthermore analysed for its dependence on or sensitivity to variations in the following parameters:

• Natural Gas price:	Sensitivity	Base Case -/+40%	
• CO_2 emission quota market price	Base case:	0	\$ / ton CO_2
	Sensitivity:	40	\$ / ton CO_2
• Capacity assignment: assignment	Base case:	130	MW
	Sensitivity:	100MW <--> 180MW	
• Lifetime of initial investment:	Base case:	25	years
	Sensitivity:	20	years
• Rate of calculation (interest rate)	Base case:	4.0	% p.a.
	Sensitivity:	10.0	% p.a.
• Initial investment (CAPEX)	Sensitivity:	Base Case +/- 20%	

The combined steam turbine (ST) and gas turbine (GT) capacity in the KSA HYSOL configuration plant has been assigned a total combined capacity of 130MW. The peak power generated by the plant is limited to 130 MW, and the plant is made to follow a demand curve congruent or analogous to that of country altogether. This implies that the number of full load hours for the combined KSA HYSOL configuration can be calculated as 812.7GWh/130MW = 6251 hours/year, and the demand coverage rate is above 99.9%.

2.4. Electricity costs as function of load factor and NG price

In Figures 1-4 results on the LCOE (given along the y-axis) are shown as a function of the annual load. The annual load or electricity production, - here expressed through its equivalent, the number of full load hours per year, is shown along the x-axis. HYSOL plant operation at different load factors is assumed to maintain the relative ST and GT contribution to the electricity production. Thus, even the annual power production may differ from the Base Case assumption the %-split of production contributions from the ST and GT HYSOL plant components is assumed constant. And the share of the annual production based on gas (via the GT directly and indirectly via GT flue gas heat recovered and utilized by the ST) is kept constant.

Furthermore, for this feasibility analysis the HYSOL plant operation efficiency is assumed constant, - even at e.g. lower annual production levels. And gas consumption per MWh electricity generated, accordingly, is assumed constant and independent of the production. This may be a somewhat rough assumption.

Design Point assumptions

Assumptions used as basis for optimizing and configuring the HYSOL plant, will in the following be termed the 'Design Point' data assumptions. Yellow points, 'Design Points', shown in Figures 1-4 represent results for the KSA HYSOL plant based on Base Case assumptions. Black points, correspondingly, represent (OCGT or CCGT) reference technology results based on equivalent assumptions. Other results presented may thus be considered as sensitivity and parameter analyses.

3. HYSOL relative to OCGT and CCGT

In what follows the KSA HYSOL plant alternative is compared to competing 'conventional' or reference plant solutions based on equivalent system framework condition. Benchmarked via the LCOE the competing technologies are evaluated using equivalent general assumptions. The so-called Base Case data assumptions form the core for this feasibility comparison. For selected key parameters LCOE consequences of data deviating from Base Case are covered via sensitivity analyses.

Competing reference technologies assumed are the Open Cycle Gas Turbine (OCGT) and the Combined Cycle Gas Turbine (CCGT).

For consistency of the comparison it is assumed, that the average annual electricity production is the same for the HYSOL alternative and for the reference plants. Furthermore, plants being compared are assumed to have the same capacity value in the KSA power system, and the plants are assumed to be fully dispatchable (firm power). Thus, all plants are assumed to be able to occupy the same position in the overall power system dispatch.

Data for the KSA HYSOL alternative and for the assumed KSA OCGT and KSA CCGT reference power plants are found in the Appendix.

It can be observed from Figures 1-4 that the annual number of full load operation hours for the HYSOL plant, shown along the x-axis, is extremely important for the electricity production cost achieved, - and the plant economy. Low annual power production results in high production costs. For the overall economy of a HYSOL plant, therefore, it is very important to achieve high annual power production, as the total production costs are much dominated by high initial investments. Natural gas prices, however, have minor impact on the HYSOL power production cost due to the relatively low electricity production contribution via the GT part of the KSA HYSOL configuration.

<u>CO_2 emission costs</u>

Comparison of HYSOL solutions relative to conventional OCGT and CCGT power plant solutions are carried out for cases with and without inclusion of an assumed CO_2 emission cost. For this sensitivity analysis it has been assumed, as an example, that CO_2 emission costs amounts to 40\$/tonCO_2 emitted. For natural gas (NG) this CO_2 emission cost is equivalent to 8.17\$/MWh NG. The CO_2 emission cost assumed thus rises the NG price with an extra 8.17\$/MWh NG.

3.1. Results: HYSOL compared to OCGT

HYSOL and OCGT: Assuming 0 \$/ton CO_2 emitted

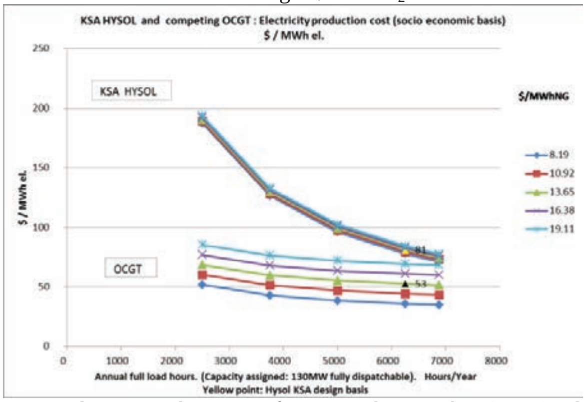


Figure 1 Electricity production costs for Open Cycle Gas Turbine (OCGT) and KSA HYSOL configuration, as function of load factor and NG price. Assumed: CO_2 costs = 0\$/tonCO_2, R=4%p.a., Lifetime=25years. Unit: \$/MWh el.

HYSOL and OCGT: Assuming 40 \$/ton CO_2 emitted

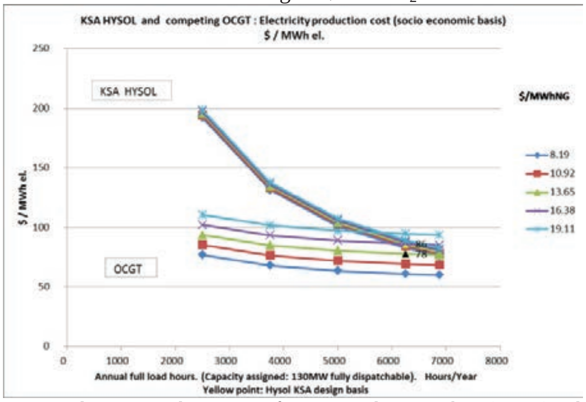


Figure 2 Electricity production costs for Open Cycle Gas Turbine (OCGT) and KSA HYSOL configuration, as function of load factor and NG price. Assumed: CO_2 costs = 40\$/tonCO2, R=4%p.a., Lifetime=25years. Unit: \$/MWh el.

3.2. Results: HYSOL compared to CCGT

HYSOL and CCGT: Assuming 0 \$/ton CO_2 emitted

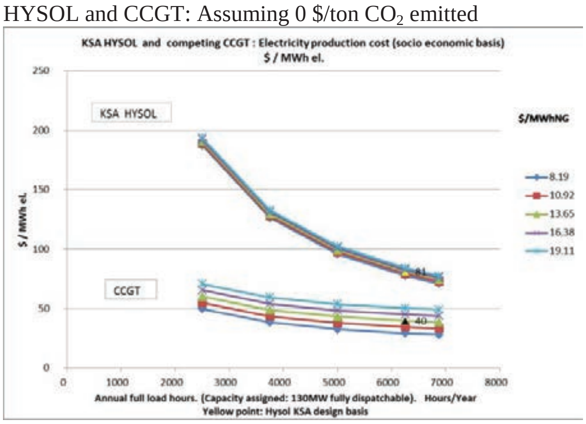


Figure 3 Electricity production costs for Combined Cycle Gas Turbine (CCGT) and KSA HYSOL configuration, as function of load factor and NG price. Assumed: CO_2 costs = 0\$/tonCO_2, R=4%p.a., Lifetime=25years. Unit: \$/MWh el.

HYSOL and CCGT: Assuming 40 \$/ton CO_2 emitted

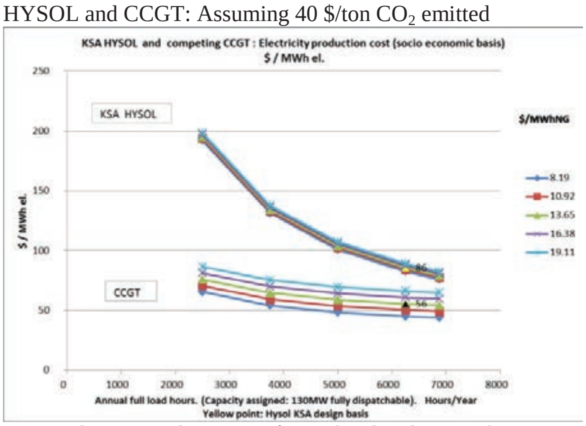


Figure 4 Electricity production costs for Combined Cycle Gas Turbine (CCGT) and KSA HYSOL configuration, as function of load factor and NG price. Assumed: CO_2 costs = 40\$/tonCO2, R=4%p.a., Lifetime=25years. Unit: \$/MWh el.

3.3. Power price composition

LCOE results based on Design Point assumptions (shown as yellow and black points in Figures 1-4) are presented below with a breakdown or split into its components related to respectively Investment, O&M, and Fuel cost parts.

HYSOL

Table 1 KSA HYSOL alternative: Electricity production cost (LCOE on socio economic basis) for 'design basis' assumptions split on contributions from the Investment, O&M, and Fuel Cost parts to the total cost.

Electricity production costs (LCOE) split on cost components							
at 'design basis point' data		Investment		O & M		Fuel costs	
Total							
$/MWh el	**% of tot**	$/MWh el	% of tot	$/MWh el	% of tot	$/MWh el	% of tot
81.09	**100.0%**	60.91	75.1%	12.13	15.0%	8.05	9.9%

OCGT

Table 2 KSA 130MW OCGT reference: Electricity production cost (LCOE on socio economic basis) for 'design basis' assumptions split on contributions from the Investment, O&M, and Fuel Cost parts to the total cost. OCGT capacity: 130MW.

Electricity production costs (LCOE) split on cost components							
at 'design basis point' data		Investment		O & M		Fuel costs	
Total							
$/MWh el	**% of tot**	$/MWh el	% of tot	$/MWh el	% of tot	$/MWh el	% of tot
52.66	**100.0%**	8.31	**15.8%**	2.30	**4.4%**	42.05	**79.8%**

CCGT

Table 3 KSA 130MW CCGT reference: Electricity production cost (LCOE on socio economic basis) for 'design basis' assumptions split on contributions from the Investment, O&M, and Fuel Cost parts to the total cost. CCGT capacity: 130MW.

Electricity production costs (LCOE) split on cost components							
at 'design basis point' data		Investment		O & M		Fuel costs	
Total							
$/MWh el	**% of tot**	$/MWh el	% of tot	$/MWh el	% of tot	$/MWh el	% of tot
39.93	**100.0%**	10.16	**25.4%**	3.41	**8.6%**	26.36	**66.0%**

Table 1 illustrates, as expected, that power production costs from the KSA HYSOL plant are dominated by the investment cost component. On average for the period analysed of about 75% of the total electricity costs relates to the initial investment, whereas the fuel cost component only contributes about 10% to the total costs. Compared to results for OCGT and CCGT plants shown in Table 2 and Table 3, this illustrates that HYSOL plants are less exposed and less vulnerable to gas price (and CO_2 emission cost) uncertainty.

4. Sensitivity analyses and conclusions

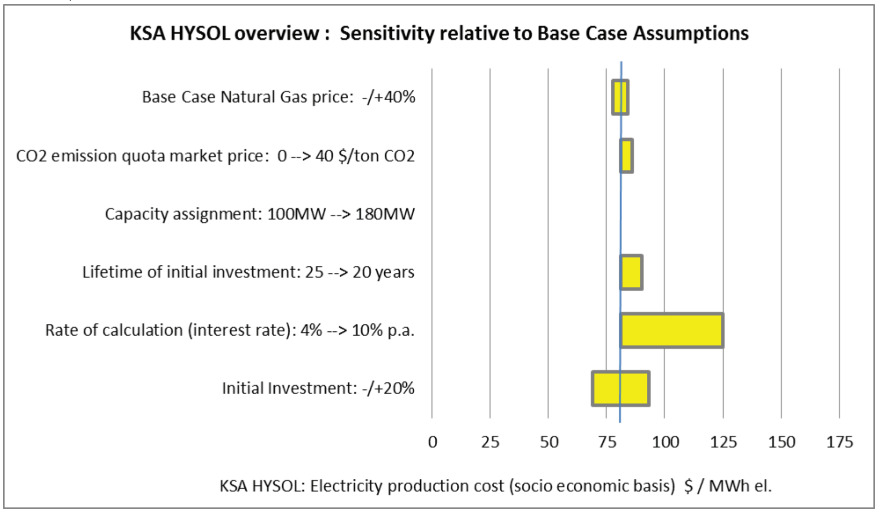
4.1. Overview of sensitivity analyses

Sensitivity analyses shown in Tables 4-7 describe how power productions costs (LCOE) deviate from results based on Base Case and 'design point' assumptions, if one parameter only is changed at a time.

Blue vertical lines in Tables 1-3 represent the LCOE calculated from Base Case assumptions. Tables 1-3, shown above, thus give details on the Base Case results, that are 'starting points' for the sensitive analysis results shown below, - for the KSA HYSOL, KSA OCGT and KSA CCGT plants respectively.

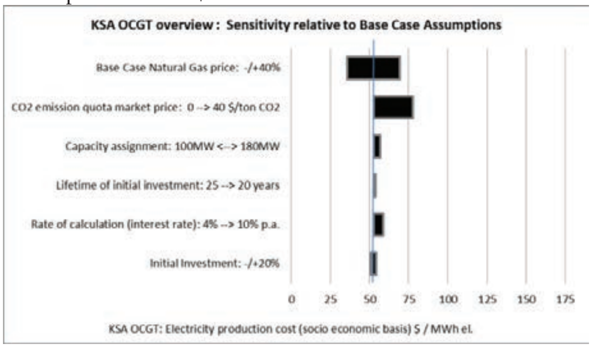
KSA HYSOL

Table 4 KSA HYSOL results in overview: Electricity production costs (LCOE) - Sensitivity relative to Base Case Assumptions. Units: $/MWh el.



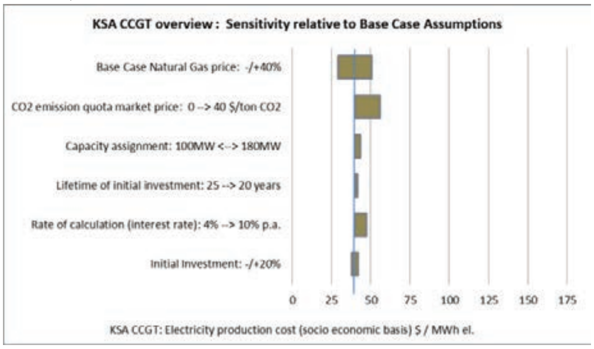
KSA OCGT

Table 5 KSA OCGT results in overview: Electricity production costs (LCOE) - Sensitivity relative to Base Case Assumptions. Units: $/MWh el.



KSA CCGT

Table 6 KSA CCGT results in overview: Electricity production costs (LCOE) - Sensitivity relative to Base Case Assumptions. Units: $/MWh el.



4.2. Conclusions

The price of natural gas (NG) and its expected development strongly impacts the economic attractiveness of HYSOL solutions relative to NG based competing technologies, such as OCGT and CCGT power plants.

CO_2 emission costs acts heavily in favour of HYSOL solutions. As seen from Tables 4-6 (as expected) in particular an OCGT plant solution is strongly exposed to potential rising CO_2 emission costs.

The capacity of a HYSOL plant is defined by the size of firm capacity it may substitute being part the power system in question (KSA). This impacts the required capacity investments for competing solutions (OCGT or CCGT) matching the HYSOL plant in the system. The economic implication of different capacity assignments, however, as seen from Tables 4-6, is relatively minor. This due to the relative low initial investment component for OCGT and CCGT plants, which may be seen comparing power price composition results shown in Tables 1-3.

The period analysed and the lifetime of the initial investments has minor impact on the electricity production cost for the

OCGT and CCGT plant solutions. Being an initial investment intensive RES based technology the HYSOL solution is seen to be impacted, though moderately, from changes in lifetime of the investment.

The interest rate or the rate of calculation is important for initial investment intensive plants, such as the HYSOL solution. In Base Case a rate of calculation of 4% p.a. has been assumed, which may correspond to typical socio-economic conditions. Assuming a higher rate of interest of 10% p.a., that may resemble a corporate economic situation, it is seen from Table 4 that power production costs (LCOE) are increased substantially. Thus, in particular the HYSOL solution is very sensitive to changes in the interest rate.

HYSOL solutions, being investment intensive are as such very sensitive to changes in the overall investment costs, and the rate of interest, whereas the OCGT and CCGT solutions are considerable less exposed to changes in the overall investment.

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Appendix A.

KSA HYSOL: *CAPEX & OPEX* [1,2,3,4]

Lump costs

CAPEX:	OPEX:
Power block: 124 M$	Water consumption: 240.000 m3/year @ 2.3 $/m3
Solar field and TES: 470 M$	NG consumption: 32.250 Tm/year @ 4 $/MBtu
BoP and miscellaneous: 109 M$	Spare parts: 0.67% of CAPEX/year
Indirect costs: 70.3 M$	Staff: 44 persons @ 65.000 $/year
TOTAL: 773.3 M$	Land rental, insurance and other costs: 1.25 M$/year

KSA OCGT: *CAPEX & OPEX* [1,2,4]

Lump costs

CAPEX:	OPEX:
Power block: 39.1 M$	Water consumption: - m3/year
Solar field and TES: - M$	NG consumption: 150.800 Tm/year @ 4 $/MBtu
BoP and miscellaneous: 51.4 M$	Spare parts: 0.5% of CAPEX/year
Indirect costs: 9.1 M$	Staff: 17 persons @ 72.000 $/year
TOTAL: 99.6 M$	Land rental, insurance and other costs: 0.15 M$/year

KSA CCGT: *CAPEX & OPEX* [1,2,4]

Lump costs

CAPEX:	OPEX:
Power block: 61.7 M$	Water consumption: 24.000 m3/year @ 2.3 $/m3
Solar field and TES: - M$	NG consumption: 106.100 Tm/year @ 4 $/MBtu
BoP and miscellaneous: 59.4 M$	Spare parts: 0.5% of CAPEX/year
Indirect costs: 12.1 M$	Staff: 27 persons @ 69.000 $/year
TOTAL: 133.1 M$	Land rental, insurance and other costs: 0.20 M$/year

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